7

Klystrons

Conventional electronic vacuum tube failed to operate above 1GHz

The principal limitations of conventional negative grid electron tubes are :

1. Electron transit time which becomes a noticeable proportion at high frequencies.

2. Lumped electrical reactances and law Q resonant circuits. There are some severe limitations on conventional tubes which make their operation relatively poor at UHF and VHF.

The multicavity klystron and for that matter the various devices described in this chapter and the following chapter are based on the principal that "if you cannot break them, join them"; *i.e.* to say that the transit time effect which forbids the use of conventional tubes at UHF/VHF is put to effective use in the operation of devices like Klystron, Magnetron etc.

TWT → Travelling Wave Tube.

7.1. Klystron

A klystron is a velocity modulated tube, in which the velocity modulation process produces a density modulated stream of electrons. The earliest form of velocity variation device is the "Two cavity klystron amplifier", whose schematic diagram is shown in Fig. 7.1. It is seen that a high velocity electron beam is formed, focussed and sent down along glass tube to a collector electrode, which is a high positive potential with respect to the cathode. Magnetic focussing is used here, but the arrangement has not been shown in the figure for the sake of simplicity. As it is clear from the schematic Fig. 7.1 a two cavity klystron amplifier consists of a cathode, focussing electrodes, two buncher grids separated by a very small distance forming a gap *A*, two catcher grids with a small gap *B* followed by a collector. The significance of buncher and catcher grids will be clear from the following discussion.

The input and output are taken from the tube *via* resonant cavities (refer to chapter on microwave components for details). The separation between buncher grids and catcher grids is called *drift space*. The electron beam passes gap *A* in the buncher cavity to which RF signal to be amplified is applied and is then allowed to drift freely without any influence from Rf. fields until it reaches gap *B* in the output or catcher cavity.

gap B followed by collector

Cathode

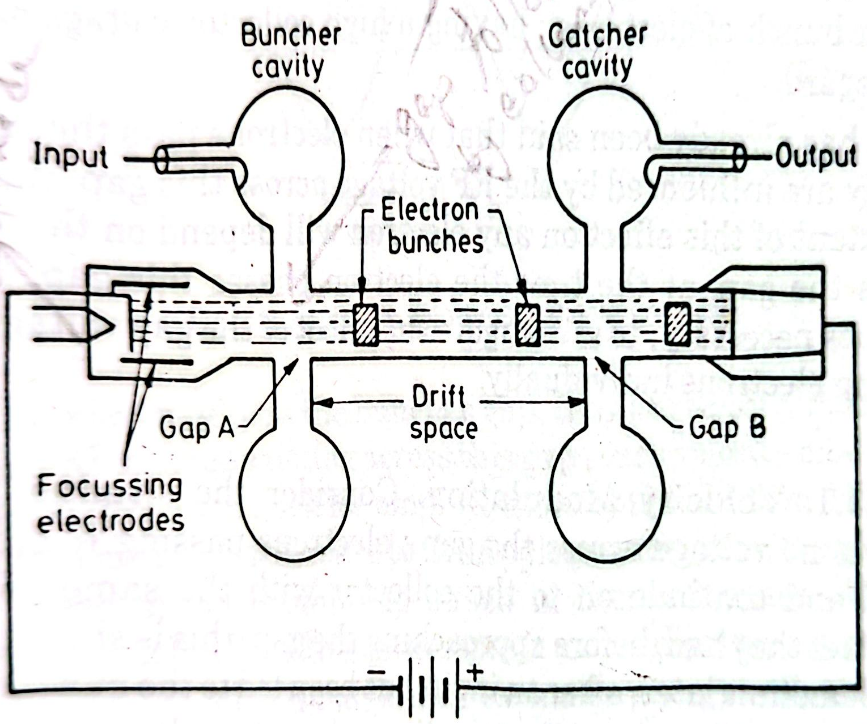

Fig. 7.1. Schematic diagram of a klystron amplifier.

The first grid (focussing grid) controls the number of electrons in the electron beam and serves to focus the beam. The velocity of electron in the beam is determined by the beam accelerating potential. On leaving the region of first grid, the electrons pass through the grids of buncher cavity. The grids of the cavity allow the electrons to pass through, but confine the magnetic fields within the cavity. The space between the grids is referred to as *interaction space*. When electrons travel through this space they are subjected to RF potentials at a frequency determined by the cavity resonant frequency or the input frequency. The amplitude of this *RF* potential between the grids is determined by the amplitude of the incoming signal in case of the amplifier, or by the amplitude feedback signal from the second cavity if used as an oscillator. If all goes well, oscillations will be excited in the second cavity which are of a power much higher than in the buncher cavity, so that a large output can be taken.

As it is seen that the cavities are re-entrant type and are also tunable. Further more, they may be integral or demountable; in the latter case the wire grid meshes may be connected to the rings external to the glass envelope, and cavities may be attached to the rings. Although the drift space is quite long and the transit time in it is put to use, the gaps must to be short that the voltage across them does not change significantly during the passage of a particular bunch of electrons ; having a high collector voltage helps in this regard.

It has already been said that when electrons pass through gap A, they are influenced by the RF voltage across this gap. However, the extent of this effect on any electron will depend on the voltage across the gap, at the time the electron passes this gap. It thus becomes necessary, to investigate the effect of the gap voltage upon passing electrons individually.

7.1.1. Velocity Modulation. Consider the situation when there is no voltage across the gap ; electrons passing it are unaffected and continue on to the collector with the same constant velocities they had, before approaching the gap (this is shown in Fig. 7.2). Sometime later, after an input has been fed to the buncher grid, an electron will pass gap A at the time when the voltage across this gap is zero and going positive, let this be the reference electron y. This reference electron is unaffected by the gap, as evidenced by the fact that it has the same slope on the "Applegate diagram" of Fig. 7.2, as electrons passing the gap before any signal was applied to the buncher cavity.

Another electron z, passes the gap slightly later than y, as shown. In absence of gap voltage, both electrons would have continued past the gap with unchanged velocity and, therefore, neither would have caught up with the other. In presence of positive voltage across gap A, however electron z is accelerated slightly and given enough time, will catch up with the reference electron y easily before gap B is approached. Similarly, electron x passes gap A slightly before the reference electron, and is retarded by the negative voltage, at that instant across the gap ; since electron y was not so retarded, it has an excellent chance of catching electron x, before gap B, and this is done as shown in Fig. 7.2.

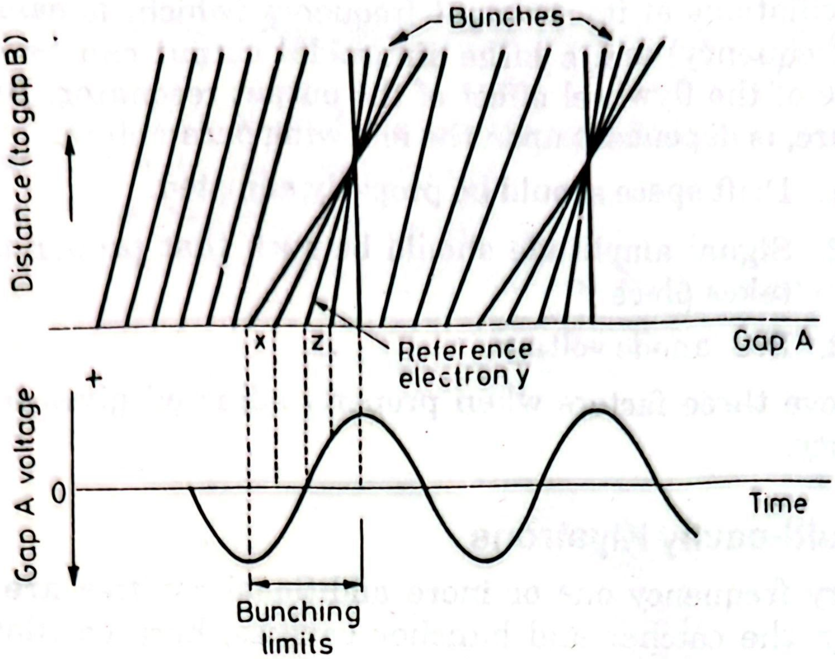

Fig. 7.2. Applegate diagram for klystron amplifier.

As electrons pass the buncher gap, they are *velocity modulated* by the RF voltage existing across this gap ; such velocity modulation is not sufficient in itself for amplification, by the klystron. However, as explained with reference to the Applegate diagram, the electrons are given an opportunity to bunch in the drift space. When an electron catches up with another one,it may simply pass it and forge ahead ; on the other hand, it may exchange energy with the slower electron, giving it some excess energy, and the two bunch together and move on with the average velocity of the beam. As the beam progresses further down along the drift space, the bunching becomes more complete, as more and more of the faster electrons catch up with bunches ahead. Eventually, the current passes the catcher gap with quite pronounced bunches and, therefore, varies cyclically with time, and this variation in current density (often called current modulation) enables the klystron to have a significant gain.

It is noted that (reference to Applegate diagram) bunching can occur only once per cycle, centering on the reference electron. The limits of bunching are also shown, any electrons arriving slightly after the second limit are not accelerated sufficiently to catch the reference electron and that the reference electron cannot catch up with any electron passing through the gap *A* just before the first limit. Bunches, therefore, arrive at the catcher grid, once per cycle and then deliver energy to this cavity. The catcher cavity is excited into oscillations at its resonant frequency (which is same as the input frequency) and a large sinusoidal output can be obtained because of the flywheel effect of the output resonator. Bunching, therefore, is dependent upon the following parameters.

1. Drift space should be properly adjusted.
2. Signal amplitude should be such that proper bunching takes place.
3. D.C. anode voltage.

Above three factors when properly adjusted gives maximum efficiency.

7.2. Multi-cavity Klystrons

Very frequency one or more additional cavities are inserted between the catcher and buncher cavities, here oscillations are excited in the middle cavity by the partially bunched electron stream passing the gap *B* ; in this way a voltage is produced across *B* that also acts on the electron stream. By detuning the additional cavity so that its gap offers an impedance having an inductive component (*i.e.* resonant frequency slightly above the signal frequency), the phase of the voltage across *B* is related to the electron stream at *B* in such a manner as to cause further velocity modulation. (The schematic diagram of a 3 cavity klystron is shown in Fig. 7.3). This very considerably increases the voltage amplification of the tube and likewise raises the efficiency. It is also possible to increase the BW of a klystron amplifier by employing one or more intermediate cavities that are properly tuned.

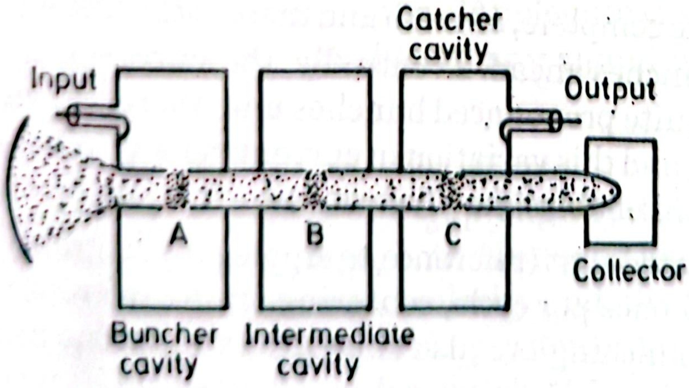

Fig. 7.3. Three cavity klystron.

7.3. Mathematical Analysis of Two Cavity Klystron

The following assumptions are made before the analysis is made:

(1) Electron transit angle in buncher and catcher grids is very small.

(2) $V_1 \leq V_o$, where V_1 is the amplitude of RF signal voltage at buncher grid, V_o is accelerating voltage.

(3) Space charge effects are neglected.

(4) Electron beam density is uniform throughout the length, *i.e.* no loss of electrons takes place in buncher and catcher grids. Analysis is now made with reference to Fig. 7.4.

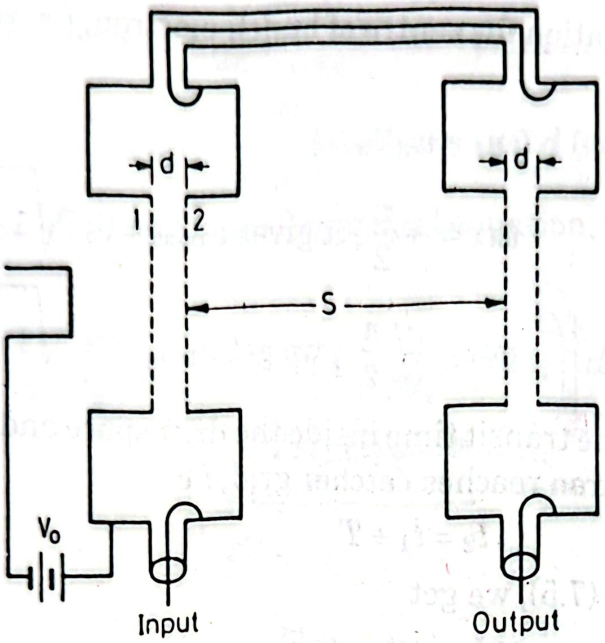

Fig. 7.4. Two cavity klystron.

In Fig. 7.4, d = Interaction gap

s = Drift space

V_o = Accelerating voltage.

We know from the very well known relation that

$$v_o = \sqrt{\frac{2eV_o}{m}} \qquad \text{...(7.1)}$$

$$\left[\because \quad eV_o = \frac{1}{2} mv_o^2\right]$$

Voltage at grid 1 = V_o

Voltage at grid 2 = $V_o + V_1 \sin \omega t_1$.

In the above relation, v_o represents electron velocity at grid 1 of buncher grid and $V_1 \sin \omega t_1$ is the feedback voltage to the buncher cavity from catcher cavity.

$\frac{1}{2}mv_1^2 = eV_0\left(1+\frac{V_1}{V_0}\right.$

$\therefore v_1^2 = \frac{2eV_0}{m}\left(1+\frac{V_1}{V_0}\sin\omega t_1\right)$

$v_1 = v_0\sqrt{1+\frac{V_1}{V_0}\sin\omega t_1}$

Also $$\frac{1}{2}mv_1^2 = e(V_o + V_1 \sin \omega t_1) \qquad \text{...(7.2)}$$

(Electrons come out of buncher grid 2 at time t_1 and velocity v_1)

From relation (7.2) and (7.1), we get

$$v_1 \equiv v_o\sqrt{1+\frac{V_1}{V_o}\sin\omega t_1} \qquad \text{...(7.3)}$$

Eq. (7.3) is obtained provided $V_1 << V_o$. This is an equation of velocity modulation for centre of bunch electron, *i.e.* when $\omega t_1 = 0$, we get

$$v_1 = v_o.$$

When $\omega t_1 = +\frac{\pi}{2}$, it gives $v_{1\max} = v_o\sqrt{1+\frac{V_1}{V_o}}$

and when $\omega t_1 = -\frac{\pi}{2}$, we get $v_{1min} = v_o\sqrt{1-\frac{V_1}{V_o}}$ ...(7.4)

Let T be the transit time inside the drift space and t_2 be the time at which electron reaches catcher grid, *i.e.*,

$$t_2 = t_1 + T \qquad \text{...(7.5)}$$

From Eq. (7.5), we get

$$\omega t_2 = \omega t_1 + \omega T \qquad \text{...(7.5a)}$$

where ωt_2 = Transit angle at catcher grid
ωt_1 = Transit angle when electrons leave buncher grid.

$$T = \frac{s}{v_1} = \frac{s}{v_o\sqrt{1+\frac{V_1}{V_o}\sin\omega t_1}} \qquad \text{...(7.6)}$$

where $\frac{s}{v_o}$ is transit time for centre of bunch electron.

$\therefore$ From Eq. (7.5 *a*) and (7.6)

$$\omega t_2 = \omega t_1 + \frac{\omega s}{v_o\sqrt{1+\frac{V_1}{V_o}\sin\omega t_1}} \qquad \text{...(7.7)}$$

or $$\omega t_2 = \omega t_1 + \frac{\alpha}{\sqrt{1+\frac{V_1}{V_o}\sin\omega t_1}} \qquad \text{...(7.8)}$$

where $\frac{\omega s}{v_0} = \alpha$ is called transit angle for centre of bunch electron and $\omega t_2 - \omega t_1 =$ transit angle inside the drift space.

Power output at catcher grid. Let $V_2 \sin \omega t_2$ be voltage at catcher grids, hence energy given by an electron is equal to $-eV_2 \sin \omega t_2 = W'$.

(Negative sign indicates that energy is given by the electron.)

Average energy given by an electron to the field (per electron)

$$\therefore \quad W/\text{electron} = \frac{1}{2\pi}\int_{\omega t_1 = 0}^{2\pi} W'\, d(\omega t_1) \qquad \text{...(7.9)}$$

$$P_{av} = \frac{1}{2\pi}\int_{0}^{2\pi} (-eV_2 \sin \omega t_2)\, d(\omega t_1)$$

From Eq. (7.8) and using binominal equation, we get

$$P_{av} = -\frac{eV_2}{2\pi}\int_{0}^{2\pi} \sin\left[\omega t_1 + \alpha\left(1 - \frac{V_1}{2V_o}\sin \omega t_1\right)\right] d(\omega t_1) \qquad \text{...(7.10)}$$

$$P_{av} = -eV_2 J_1(x) \sin \alpha \qquad \text{...(7.11)}$$

where $$x = \frac{\alpha V_1}{2V_o}$$

and is a bunching parameter for the klystron, $J_1(x) =$ Bessel function of the first order.

Fig. 7.5 gives a graph between $J_1(x)$ and x.

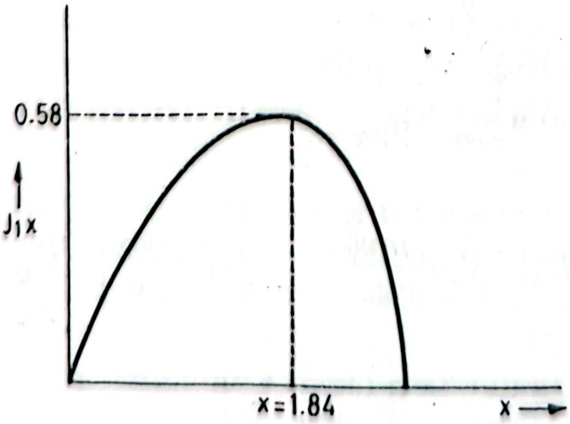

Fig. 7.5. Graph for Bessel function $J_1(x)$.

Let there be N electrons reaching the catcher.

$\therefore$ Energy transferred to the catcher/sec.

$$= N \cdot P_{av} = P_{ac}$$

$$= -NeV_2 J_1(x) \sin\alpha$$

[since current $= -Ne] = I_o]$

$$P_{ac} = -I_o V_2 J_1(x) \sin\alpha \qquad \text{...(7.12)}$$

D.C. power $P_{dc} = I_o V_o$ ...(7.13)

∴ efficiency $\eta = \dfrac{P_{ac}}{P_{dc}} = -\dfrac{V_2}{V_0} J_1(x) \sin\alpha$ ...(7.14)

For maximum efficiency,

$$J_1(x) = 0.58 \text{ at } x = 1.84,$$

and $\sin\alpha = -1$

∴ $\alpha = 2\pi n - \pi/2.$

[∵ V_2 can never exceed V_0]

∴ $$\eta_{max} = \frac{V_2}{V_0} J_1(x)$$

$$= \frac{V_2}{v_0}(0.58) = 58\%.$$ [For $V_2 = V_0$]

Value of accelerating voltage for maximum output and hence maximum efficiency. ✓

Let

$x = \dfrac{V_1 \alpha}{2V_0}$ [Put $\alpha = 2\pi n - \dfrac{\pi}{2}$ in this and $x = 1.84$ (for max. output)]

$$\Rightarrow \quad \frac{1.84 \times 2}{2\pi n - \frac{\pi}{2}} = \left(\frac{V_1}{V_0}\right)_{max}$$

$$\Rightarrow \quad \left(\frac{V_1}{V_0}\right)_{max} = \frac{3.68}{2\pi n - \frac{\pi}{2}} \qquad \text{...(7.15)}$$

From Eq. (7.1) $V_0 = \dfrac{mv_0^2}{2e}$ $\left[v_0^2 = \left(\dfrac{\omega s}{\alpha}\right)^2\right]$

$$= \frac{m}{2e}\left[\frac{\omega s}{2\pi n - \frac{\pi}{2}}\right]^2$$

∴ $$V_0 = 0.284 \times 10^{-11}\left[\frac{\omega s}{2\pi n - \frac{\pi}{2}}\right]^2 \qquad \text{...(7.16)}$$

For $n = 1$, V_0 is maximum

If $n > 1$, V_0 decreases.

From Eq. (7.15)

$$\left(\frac{V_1}{V_0}\right)_{max} = \frac{3.68}{2\pi n - \frac{\pi}{2}}$$

$$\Rightarrow \quad V_1 = \frac{3.68}{2\pi n - \frac{\pi}{9}} \times 0.284 \times 10^{-11} \frac{(\omega s)^2}{\left(2\pi n - \frac{\pi}{2}\right)^2} \quad \text{...(7.17)}$$

7.4. Performance and Applications

A multicavity klystron can be used as a medium or high power amplifier in the U.H.F. and microwave ranges, for both continuous and pulsed operation. These tubes are available over the range 250 MHz to about 60 GHz, with typical maximum CW output powers of 100 kW in the V.H.F. range and a maximum of about 250 kW in the *X* band ; pulsed peak power upto 25 MW are also available.

The power gain of multicavity klystron varies from about 30 dB at U.H.F to over 60 dB in the *X* band, with BW's from 8 to 60 MHz and mechanical tuning ranges from 300 to 600 MHz. The size of klystron depends upon the operating frequency which determines the cavity size, length of drift space and also the magnet size, and lastly the output power. A high power U.H.F. klystron may be upto 7 ft long and may weigh over 250 kg. Multicavity klystron amplifiers are very noisy in practice ; this dictates their applications, which are obviously in transmitters rather than receivers. Such klystrons are used as power output tubes in U.H.F. television transmitters, in troposphere scatter transmitters, in some satellite communications ground stations etc. These are also used for pulsed power requirements.

The two cavity klystron oscillator is used as a power oscillator in the frequency range from 5 to 50 GHz, with output powers ranging from 2 to 10 W; but as much as 200 W CW is also available from commercial devices. The main applications are in CW droppler radar, for pumping parametric amplifiers and as frequency modulated oscillators in high power microwave links. The biggest advantage of two cavity klystrons is the relatively high CW power of which they are capable as compared to their small size. The biggest disadvantage is that they require two cavities and each has to be returned separately if a frequency change is required. The cavities are, high *Q* cavities with narrow band widths, and thus individual tuning is awkward ; therefore, two cavity klystrons are generally used in fixed frequency applications. When frequency is to be varied, the lower power, lower efficiency *reflex klystron* is used instead ; it has only one cavity resonator and therefore tuning is easy.

7.5. Reflex Klystron

A reflex klystron is a low power, low efficiency microwave oscillator, illustrated schematically in Fig. 7.6. It consists of an electron gun similar to that of a multicavity klystron, a filament surrounded by a cathode and a focussing electrode at the cathode potential. The suitably formed electron beam is accelerated towards the cavity, which has a high positive voltage applied to it and thus acts as an anode. After passing the gap in the cavity, electrons travel towards repeller electrode which is at a high negative potential.

The electrons never reach this electrode because of the negative field.

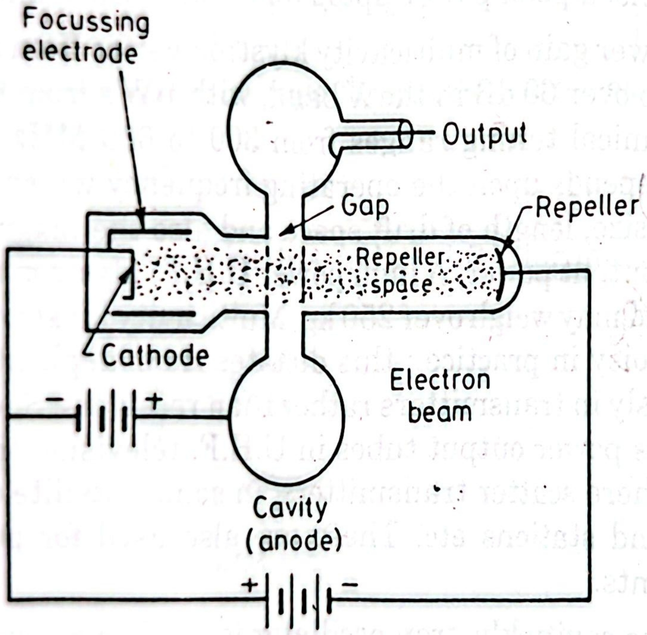

Fig. 7.6. Reflex klystron schematic.

The electrons are repelled back from midway of the repeller space by the repeller grid towards the anode ; if conditions are properly adjusted, then the returning electrons give more energy to the gap than they took from it on forward journey, and thus oscillations are sustained.

7.5.1. Operation. It is assumed here as also is the case with two cavity klystron oscillator that oscillations are capable of starting through noise or switching transients. In order to understand the operation it is advantageous to consider specific electrons, passing the gap for the first time at selected times. Here reference electron taken is *y* and it passes the gap without being affected by the voltage across it and travels towards to repeller, and is returned back to anode without touching the repeller. The fast electrons come nearer to the repeller than slow ones, and therefore take a longer time to return to the resonator gap than electrons which did not approach the repeller so closely.

The system is analogous to throwing stones upward (since the gravitational field of the earth is very similar to the field to which the electrons are subjected near the repeller) ; more forcefully a stone is thrown upward, longer it takes to come down again. Fig. 7.7 shows the Applegate diagram for a reflex klystron. It shows the path of reference electron *y*, rather the position of *y* at any instant in the repeller space ; its path of course is straight out and then straight back along the same line. Consider an electron *x* which passes the resonator gap (on its way out) slightly before the reference electron. Had there been no gap voltage, *x* would have returned before the reference electron. However, due to presence of RF voltage the electrons will be velocity modulated. Electron *x*, as seen is in fact accelerated due to the positive field available to it and so comes closer to the repeller as compared to reference electron *y*. As seen from Fig. 7.7, it is quite possible that *y* will catch up with electron *x* as they enter back into resonator gap. Similarly electron *z* leaves the gap slightly after the reference electron *y* and experiences a negative field which slows it ; therefore electron *z* does not reach as close to repeller compared to electron *y*, before it is returned back to resonator gap. There exists every possibility that electron *z* also catches up with electron *y* as it enters back into the gap. Thus all the three electrons *x*, *y* and *z* return back nearly at the same time into the resonator gap.

The system now becomes analogous to a 2 cavity klystron where velocity modulation is converted into current modulation after the electrons have left the gap on their outward journey. The bunching in reflex klystron is not as complete as in a multicavity klystron, because there are quite a few electrons arriving at the gap out of phase and contributing to the high noise and low efficiency of the device. However, bunching is sufficient between the bunching limits, to make operation possible.

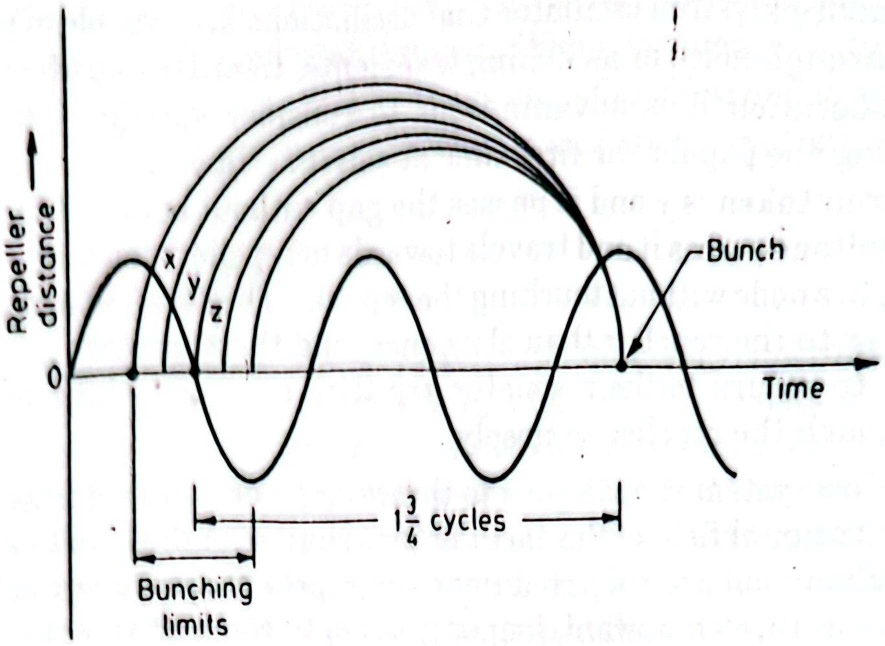

Fig. 7.7. Applegate diagram for reflex klystron in 1¾ cycle mode.

It is to be noted here that one bunch forms per cycle of oscillations around the reference electron, and that these bunches deliver energy to the gap.

7.5.2. Transit Time. For oscillations to be maintained, the time taken by the electron to travel into the repeller space and back to the gap (called transit time) must have an optimum value. This factor is not so important in a klystron amplifier, but it assumes a great importance here. Here we will see what should be an optimum correct time for the oscillations to be sustained.

The most optimum departure time is obviously centred on the reference electron which is at 180° point of sine wave voltage across the resonator gap. Actually no energy goes into velocity modulating of the electron beam. It takes some energy to accelerate electrons, but just as much energy is gained from retarding electrons ; since there are as many retarded electrons as accelerated, the total energy outlay is nil. From the above discussion it is evident that the best possible time for electrons to return to the gap is at a time at which the voltage then existing across the gap will apply maximum retardation to them ; this is when the gap voltage is positive maximum. This causes electrons to fall through the maximum negative voltage between the gap grids, thus giving up the maximum amount of energy to the gap! Thus it appears that, the best time for electrons to return to the gap is at the 90° point of the sine wave gap voltage. Referring to Fig. 7.7, returning of electrons after

$1\frac{3}{4}$ cycles satisfies the above requirements ; when generalised the transit time in repeller space is given by

$$T = n + \frac{3}{4}$$

where n = any integer.

7.6. Mathematical Analysis for Reflex Klystron

Fig. 7.8 gives the various parameters required for this analysis.

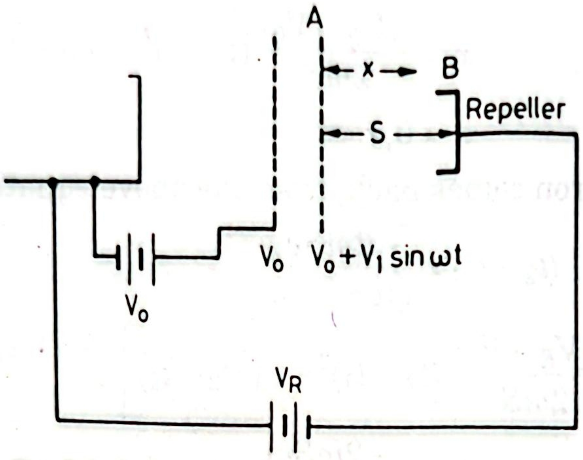

Fig. 7.8. Reflex klystron with various parameter.

Recalling Eq. (7.1)

$$v_0 = \sqrt{\frac{2V_0 e}{m}}$$

Also Eq. (7.3)

$$v_1 = v_0 \sqrt{1 + \frac{V_1}{V_0} \sin \omega t}$$

Voltage difference between points A and B is

$$V_R - (V_0 + V_1 \sin \omega t) \approx V_R - V_0 \qquad \text{...(7.18)}$$

Field between points A and B is

$$E = -\frac{(V_R - V_0)}{S} \qquad \text{...(7.19)}$$

Force $$= -eE = e\frac{(V_R - V_0)}{S} \qquad \text{...(7.20)}$$

Also Force = Mass × Acceleration.

or $$\text{Force} = \frac{md^2x}{dt^2} \qquad \text{...(7.21)}$$

Where x is any distance between points A and B starting from point A.

$\therefore$ From Eqs. (7.20) and (7.21)

$$\frac{md^2x}{dt^2} = \frac{e}{S}(V_R - V_0)$$

or
$$\frac{d^2x}{dt^2} = \frac{e}{mS}(V_R - V_0) \qquad \text{...(7.22)}$$

At $\quad t = t_1,\ v = v_1$

Integrate expression (7.22), twice and we get

$$x = \frac{e(V_R - V_0)}{2mS}(t - t_1)^2 + v_1(t - t_1)$$

At $\quad x = 0,\ t = t_2$

i.e. when electron comes back, from the above equation, we get

$$(t_2 - t_1) = \frac{-2mSv_1}{e(v_R - v_0)}$$

$$\left[\because\ 0 = \frac{e(V_R - V_0)}{2mS}(t_2 - t_1)^2 + v_1(t_2 - t_1)\right]$$

or
$$(t_2 - t_1) = \frac{-2mSv_1}{e(V_R - V_0)}$$

or
$$\omega(t_2 - t_1) = \frac{-2mSv_1\omega}{e(V_R - V_0)}$$

or
$$\omega t_2 = \omega t_1 - \frac{2\omega mSv_0}{e(V_R - V_0)}\left(1 + \frac{V_1}{2V_0}\sin\omega t\right) \qquad \text{...(7.23)}$$

(Eq. 7.23 is obtained by substituting the expression for v_1)

or
$$\omega t_2 = \omega t_1 + \alpha'\left(1 + \frac{V_1}{2V_0}\sin\omega t\right)$$

where α' corresponds to centre of bunch electron and

$$\alpha' = \frac{-2\omega mSv_0}{e(V_R - V_0)} \qquad \text{...(7.24)}$$

Here bunching parameter is

$$x' = \frac{\alpha' V_1}{2V_0} \qquad \text{...(7.25)}$$

and for sustained oscillations

$$\alpha' = 2\pi n - \frac{\pi}{2} \qquad \text{...(7.26)}$$

7.6.1. Relationship between accelerating voltage and repeller voltage. We have already discussed the following equations

$$\alpha' = 2\pi n - \frac{\pi}{2}$$

$$v_0 = \sqrt{\frac{2V_0 e}{m}}$$

or
$$v_0^2 = \frac{2V_0 e}{m} \quad ...(7.27)$$

or
$$V_0 = \frac{mv_0^2}{2e}$$

Also
$$\alpha' = \frac{-2\omega m S v_0}{e(V_R - V_0)} \quad ...(7.28)$$

or
$$(v_0)^2 = \left[\frac{\alpha'(V_R - V_0)\,e}{2\omega m S}\right]^2 \quad ...(7.29)$$

From Eqs. (7.27) and (7.29),

$$V_0 = \frac{mv_0^2}{2e}$$

$$= \frac{m}{2e}\left[\frac{\alpha'\,(V_R - V_0)e}{2\omega m S}\right]^2$$

or
$$\frac{V_0}{(V_R - V_0)^2} = \frac{m}{2e} \times \frac{e^2}{4\omega^2 m^2 S^2}\left(2\pi n - \frac{\pi}{2}\right)^2$$

or
$$\boxed{\frac{V_0}{(V_R - V_0)^2} = \frac{\left(2n\pi - \frac{\pi}{2}\right)^2 e}{8\omega^2 S^2 m}} \quad ...(7.30)$$

Since bunching parameter

$$x' = \frac{V_1}{2V_0}\alpha'$$

it implies
$$\frac{V_1}{V_0} = \frac{2x'}{\alpha'}$$

$$= \frac{2x'}{2\pi n - \frac{\pi}{2}}$$

$$P_{ac} = I_0 V_1 J_1 (x')$$

$$= \frac{2V_0 I_0 . x' J_1(x')}{2\pi n - \frac{\pi}{2}}$$

and $$P_{dc} = I_0 V_0.$$

Therefore, efficiency

$$\eta = \frac{P_{ac}}{P_{dc}} = \frac{2x' J_1(x')}{2\pi n - \frac{\pi}{2}} \quad ...(7.31)$$

Maximum efficiency is obtained at $n = 1$.

7.6.2. Relation between repeller voltage and frequency of operation of reflex klystron. From Eq. (7.30).

From Eq. (7.30),

$$(V_R - V_0)^2 = \frac{8\omega^2 . mS^2 V_0}{\left(2\pi n - \frac{\pi}{2}\right)^2 e} \quad ...(7.30)$$

Differentiating with respect to x

$$\frac{dV_R}{d\omega} = \frac{8\omega mS^2 V_0}{\left(2\pi n - \frac{\pi}{2}\right)^2 e} \times \frac{1}{(V_R - V_0)}$$

Substituting the value of $(V_R - V_0)$ from Eq. (7.30),

$$V_R - V_0 = \sqrt{\frac{8mS^2 V_0 \omega^2}{\left(2\pi n - \frac{\pi}{2}\right)^2 e}}$$

∴ We get

$$\frac{dV_R}{d\omega} = \frac{8\omega mS^2 V_0}{\left(2\pi n - \frac{\pi}{2}\right)^2 . e} \times \frac{\sqrt{(2\pi n - \pi/2))^2 e}}{\omega\sqrt{8S^2 V_0 m}}$$

or $$\frac{dV_R}{d\omega} = \sqrt{\frac{8mS^2 V_0}{\left(2\pi n - \frac{\pi}{2}\right)^2 e}}$$

or $$\frac{dV_R}{df} = \frac{2\pi S}{\left(2\pi n - \frac{\pi}{2}\right)} \sqrt{\frac{8mV_0}{e}} \quad ...(7.31)$$

A numerical example illustrates the above result which is given at a later stage in this chapter.

From the Eq. (7.31) just derived it is found that frequency and hence the transit time is dependent on the repeller and anode voltages, so that both must be carefully adjusted. Once the cavity has been tuned to the correct frequency, both the anode and repeller voltages are adjusted to give the correct value of T from the data supplied by the manufacturer. A significant rise in the power output shows that correct values of voltages have been reached. There is however a range for these voltages of say ±5 to ±10 V. Every time the cavity is returned, the anode and repeller voltages have also to be adjusted accordingly.

7.6.3. Modes. Fig. 7.9 shows the range of anode repeller voltage combinations for which oscillations will take place ; the shaded areas indicate such suitable combinations. It is viewed that oscillations are possible for a range of these voltages, and yield transit times between $1\frac{3}{4}$ and $5\frac{3}{4}$ cycles, and each value of n is said to correspond to a different *mode* for the reflex klystron oscillator. The mode used mostly is the most convenient one ; the earlier the mode, the larger the output power, which is obviously an advantage. The voltages required for earlier mode are higher leading to insulation problems and the possibility of lower efficiencies. As a result modes corresponding to $n = 2$ or $n = 3$ are used most often practically.

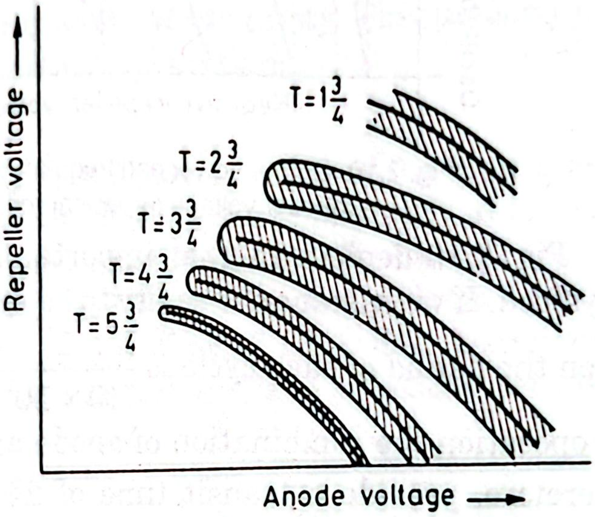

Fig. 7.9. Reflex klystron mode patterns (shaded areas show possible oscillation combinations and heavy lines show optimum combinations).

On properly tuning and a suitable voltage to anode, we can have any one of the available modes of oscillations just by adjusting the repeller voltage. The phenomenon is shown in Fig. 7.10.

The various values taken in Fig. 7.10 are just to explain the concepts. In Fig. 7.10, it is seen that maximum power output is achieved when $n = 2$. For any mode, maximum power is obtained when the repeller voltage (along with anode voltage being taken as constant) gives the optimum value of the transit time. When the repeller voltage is on either side of the correct value, the output power is less than the maximum.

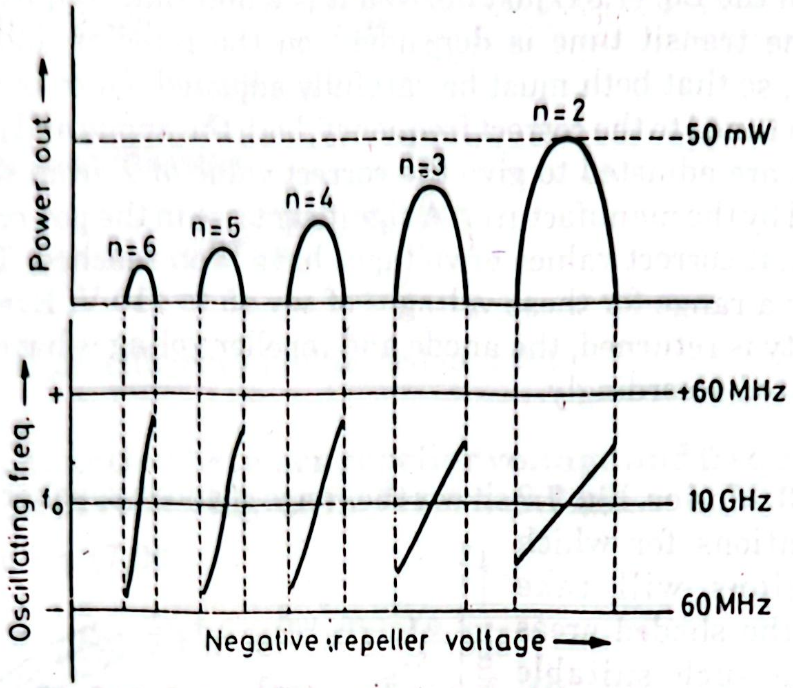

Fig. 7.10. Output power and frequency of klystron *versus* repeller voltage for typical reflex klystron.

Fig. 7.10 depicts another important characteristic of a reflex klystron. If we assume the cavity to be exactly resonant at 10 GHz, then the period of each cycle is $\frac{1}{(10 \times 10^9)} = 10^{-10}$ sec ; with mode 2 in operation the combination of anode and repeller voltages must, therefore, provide a transit time of $2\frac{3}{4} \times 10^{-10} = 275$ p sec (pico second). If the repeller voltage is a little low, the actual transit time might be 280 p sec ; rather than oscillating at 10 GHz with a slightly lower power, the klystron will operate at the frequency for which 280 p sec corresponds to 2¾ cycles, assuming that the cavity BW allows this. The new frequency will be 9.83 GHz, *i.e.* somewhat below the resonant frequency. This shows that reducing the repeller voltage alone reduces the frequency of oscillation of the reflex klystron and *vice versa.*

Example 7.1. *A reflex klystron is to be used at 2 GHz. The repeller voltage is 2 kV, accelerating voltage = 500 V, output amplitude required is 5 V. Calculate change in frequency if repeller voltage gets varied by 2%. The operation is for n = 1, S = 2 cm.*

Solution. From Eq. (7.31)

$$\frac{dV_R}{df} = 2\pi \times \frac{2}{100} \times \frac{2}{3\pi} \sqrt{\frac{8 \times 9 \times 10^{-31} \times 500}{1.6 \times 10^{-19}}}$$

$$= 4.05 \times 10^{-6}$$

$$df = \frac{dV_R}{4.05 \times 10^{-6}}$$

$$= \frac{2}{100} \times 2000 \times \frac{10^6}{4.05}$$

$$= 10 \text{ Mc/s. } \textbf{Ans.}$$

When the repeller voltage is varied slightly, it is no longer of the correct value to give $t = n + \frac{3}{4}$ at the centre frequency, but this means, of course, that the transit time has now the correct value at some nearby frequency at which oscillations will take place if this frequency is within the band width of the cavity. This property of the klystron has many important applications.

7.6.4. Performance. Reflex klystron is one of the most commonly used microwave devices. These are commercially available for frequencies ranging from under 4 to over 200 GHz. Typical power outputs range from 10 mW to 2.5 W, maximum available figures ranging from 2 W at 5 GHz to 1.5 W at 12 GHz. Efficiencies are fairly low (under 10 per cent) but this is not so significant for low power applications.

7.6.5. Tuning. The method consists of moving in or out a small screw which in turn operates on an arm that tightens or loosens small bellow ; which tighten or loosen a wall of the tuning cavity thus changing the size and frequency of resonance of the tuning cavity.

Electronic tuning is the most common type of tuning in which the repeller voltage is varied which has already been described in detail before.

7.6.6. Repeller protection. It is very important to ensure that the repeller of the reflex klystron never draws current ; if it does ever do so, it would be quickly destroyed due to the impact of high velocity electrons as well as over heating. To avoid this a cathode resistor is often used to ensure that the repeller can never be more positive than the cathode, even if the repeller voltage fails. Also the system in so arranged so that negative voltage is applied to the repeller before positive voltage appears at the anode. Usually a protected diode is connected across the klystron (with the diode's